Charge Breeding simulations in a hollow Electron beam

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INTRODUCTION

Radioactive ion beams (RIBs) are an important tool for experiments at the foremost frontier of nuclear physics. Recently, the design study final report of the European project EURISOL has been published [1]. In that report, the design of a European ISOL type facility capable of producing RIBs with intensities several order of magnitude greater than those available today has been presented. One of the important problem studied in the EURISOL design, among others, was how to reach higher efficiency in the RIB post-acceleration. In fact, since the cost of an accelerator is roughly related to the inverse of the charge state of the beam to be accelerated, a higher ion charge state for the RIB (at the injection) can sensibly reduce the cost of the accelerator . To this end, an appropriate device capable of increasing the ion charge state of the radioactive elements, has to be designed.

The EURISOL design study report has also confirmed that charge breeding can be based on two different type of ion sources: the Electron Beam Ion Sources (EBIS) and the Electron Cyclotron Resonance Ion Sources (ECRIS) [1]. The Rex-ISOLDE experiment, in fact, had already shown that the charge breeding of radioactive beams, injected as 1+, is possible with efficiency typically up to *10%* and breeding times of *~50 ms* for light beams and *~150 ms* for heavy beams. In order to become comparable, in terms of overall efficiency, with the 'classical' more expensive stripper scheme, all steps of the breeding process have to be optimized. The possibility of optimizing the charge breeding process through several techniques had been also explored within the European project EURONS-JRA3 [2]. A comparison between the two types of 'charge breeders', the EBIS and the ECR based, is also presented in [2]. In that work the advantages and the drawbacks of both devices have been analysed. It is concluded that one of the main problem of an EBIS-based 'charge breeder', for high RIB intensities, is the impossibility to be operated in CW. In ref. [3] a new version of EBIS that, at least in principle, could allow CW operation has been proposed and built for a test experiment. Practically, it consisted of a typical EBIS whose electron gun is equipped with an hollow cathode. That kind of e-gun, in fact, would allow a continuous injection of 1+ ions from the e-gun side and, as usual, the extraction of the n+ ions from the electron collector side.

Although, in principle, the hollow radius, r_h, in the electron beam (*eb*) of that EBIS could be reduced to zero by a sufficiently high focussing solenoid field, a reduction of the efficiency in charge breeding should be expected. Since such an efficiency is very important for a high-intensity RIB acceleration, a more quantitative analysis of the effect has to be performed. In this paper, loss of charge breeding efficiency due to the hollow *eb* has been studied by simulating the ion motion inside the hollow gun EBIS. The simulations were carried out by using the code BRICTEST [4] already developed for studying the ion selective containment in a EBIS with RF quadrupoles. In order to take into account the effect of an hollow *eb* in the charge breeding, the BRICTEST code, has been modified, as discussed here below.

THE BRICTEST CODE

The BRICTEST code, developed in Bari INFN section few year ago [4] to study the ion motion stability inside a test EBIS device (BRIC [6]) which had rf quadrupole electrodes for selective containment, can be also used for studying the ion charge breeding efficiency with an *eb* having a small hole inside. The ion motion equations shown in ref. [4], in fact, are still valid when the quadrupole electrode voltages, V (rf voltage) and U (dc voltage), are set to zero. However the space charge term, already present in the equations, had to be modified to take into account the eventual hollow in *eb*, with radius r_h. By taking into account those changes, the motion equations can be re-written as:

$$\begin{cases} \frac{d^2x}{d\tau^2} - b\frac{dy}{d\tau} + cx = 0 \\ \frac{d^2y}{d\tau^2} + b\frac{dx}{d\tau} + cy = 0 \end{cases} \quad \text{for } r < r_b$$

$$\begin{cases} \frac{d^2x}{d\tau^2} - b\frac{dy}{d\tau} + \left(c\frac{r_b^2}{r^2}\right)x = 0 \\ \frac{d^2y}{d\tau^2} + b\frac{dx}{d\tau} + \left(c\frac{r_b^2}{r^2}\right)y = 0 \quad \text{for } r \geq r_b \end{cases} \tag{1}$$

where:

$$\tau = \frac{1}{2}\omega t; \tag{2}$$

and with the parameter:

$$b = \frac{2q_i B}{m_i \omega}$$

(with q_i and m_i ion charge and mass respectively), related to the solenoid field B. However, in the present case, a new space charge parameter has to be introduced:

$$c = \left(\frac{1}{4\pi\varepsilon_o}\right)\frac{8q_i}{m_i\omega^2(r_b^2 - r_h^2)}\frac{I_e}{v_e}$$

where r_h is the hollow radius inside the *eb* .

The parameter τ is used instead of the time t for 'historical reason' (the code has been developed for rf selective containment and ω was the rf frequency). Furthermore, in the region where $r<r_h$ no space charge force is felt by the ions. In that region, then, only the solenoid magnetic field needed for eb focusing will act on the ions.

Apart for following the ion motion in the EBIS trap, the code BRICTESTcomputes the ion charge state breeding evolution through the following equation system:

$$\frac{dn_i}{d(j_e t)} = \frac{1}{e}[n_{i-1}\sigma_{ion,i-1\to i}(E_e) - n_i\sigma_{ion,i\to i+1}(E_e) + n_{i+1}\sigma_{RR,i\to i-1}(E_e) - n_i\sigma_{RR,i\to i-1}(E_e)] \tag{2}$$

where n_i is the ion density with charge state i, j_e the electron current density, e the electric charge and E_e the electron beam energy. Furthermore, $\sigma_{ion,i}$ and $\sigma_{RR,i}$ indicate, respectively, the ionization to the charge state i and the radiative recombination cross sections.

In general, the 'charge breeding' calculation is carried out simply by assuming as fixed the 'overlap' region between the electron and the ion beam transverse sections. Notice that in equations (3) a complete 'overlap' is assumed. In the case of a partial 'overlap', instead, each term of (3) has to be multiplied by a factor (F_{ov}) that takes into account the part of the ion beam cross section that it is not hit by the electrons. To evaluate that factor we consider a transverse *eb* section size given by $S_b=\pi r_b^2$ and assume $S_b=S_i$ (ion beam transverse size). If S_h is the cross-sectional area of the hollow beam, the mentioned factor will be given by $F_{ov}= S_h/S_b$. In term of the radii, being $S_h=\pi(r_b^2-r_h^2)$, $F_{ov}=(1-r_h^2/r_b^2)$. Then for $r_h/r_b= 0.2$ $F_{ov}=96\%$ (a reduction of 4%).

The assumption of a fixed 'beam overlap' can be a good approximation when the 1+ ion beam is injected in the *eb* with practically the same radius and with a low transverse velocity than usual. When a hollow *eb* is used, however, the above approximation is no more valid and the charge breeding calculation has to take into account that the ions oscillate in the *eb* potential well. For a while, in fact, the ions could move also in the hollow region where they cannot be hit by electrons and, as a result, their charge cannot increase during that time. In order to make more accurate 'charge breeding' calculations the code has to take into account the above mentioned transverse oscillating ion motion.

The original code BRICTEST, had already, in its first version, the possibility to follow the ion motion and check if their positions were outside the *eb* transverse size. In that case, those ions were not considered for charge breeding in the equations (3), where, to this purpose, the initial ion density n_i was properly updated. To take into account the effect of the hollow region inside the *eb* for the ion charge state evolution calculation, a check has to be performed if the ions are inside the hollow region and, in that case, exclude them as well in the calculations of the charge state increase. Furthermore, since the code cannot follow the motion of too many ions, to avoid a too long calculation time, only a fraction of them has to be followed in their motion, typically 4000. That number seems big enough to understand ion behaviors in the EBIS trap but it is too small, for statistical reason, to be used in the calculation of n_i in the equations (3). For that reason, each ion, followed in its motion through (1), has been multiplied by a factor N (typically, 5000 seems enough), when the n_i are computed through (3). The total number of ions for which the charge state evolution is computed, is typically of about $2x10^7$. In short, the modified code acts in the following way: it generates a 1+ ion distribution, flat in transverse positions and velocities, with the maximum transverse position given by r_b and the maximum transverse velocity obtained by multiplying the longitudinal velocity by a factor *vfac* chosen by the user . A check is then performed to determine which ions are inside the *eb* hollow part and excludes them from being considered for charge state evolution, by updating the n_i in eq.s (3). Finally, all ions are propagated in the EBIS trap by means of the eq.s (1) and after each integration step a new check is performed on the ion positions in order to properly re-update the n_i of eq.s (3), and compute the correct ion charge state distribution.

Another implementation that has been done to the BRICTEST code with respect to description in the original paper, has been the inclusion of the space charge compensation effect as reported in ref. [7]. The space charge compensation has been modelled in the code by using in the above mentioned space charge term *c* a factor *Cf* (when the *Cfl* flag is on). That factor is given by the relation:

$$Cf = Cfmax\,[1-exp(-t/t_0)]$$

where *Cfmax* is the maximum reachable space charge compensation (depending on the ion temperature) and t_0 is a constant time properly chosen to simulate the time extent of the compensation effect.ions for which the charge state evolution is computed, is typically of about $2x10^7$.

CODE TEST AND SIMULATION RESULTS

All the simulations shown in the following are carried out for 1+ ions of *Xe 131* and use an eb radius of *1.2 mm*.

Figure 1 shows the results of the charge state evolution simulations with a fixed 'overlap' of *96%*, corresponding to an r_h of *20%* with respect to r_b (a reference value for our E-gun design [3]). For comparison, the case of an *eb* without hole is considered. The results show that, although r_h is not so small, only a very slight difference can be noticed between the two ion charge state simulations. However, as already noticed, in the case of a hollow *eb*, the fixed 'overlap' assumption could be a very rough approximation. A more accurate ion charge state distribution evolution calculation can be carried out by using the new featu-

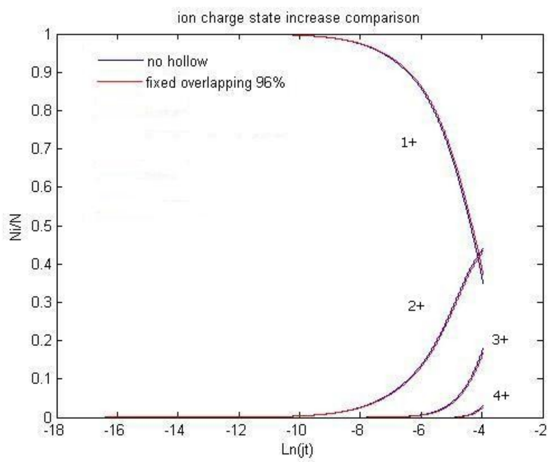

Fig.1

res of the code described in the previous paragraph. However, before that, test simulations had to be carried out in order to verify if the modified code still gave reliable results. To this purpose, test particles, for which the trajectories at all simulation time are stored, have been used. Through the test particle trajectories, in fact, one could monitor if the ion motion was consistent with the involved forces.

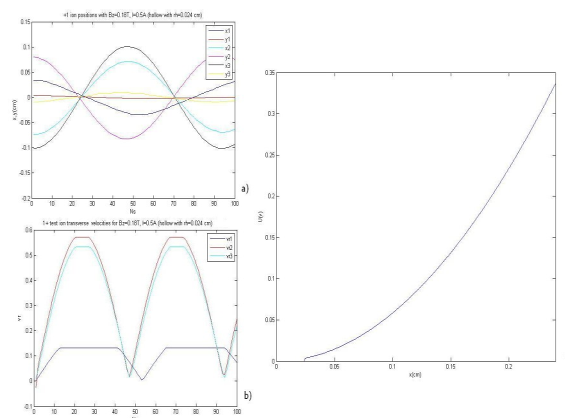

Fig.2

The routine used to solve the motion equations (1) [4] could no more work when all the force terms, except the solenoid field, are put to zero. As first test, then, we have verified that the 1+ ion motion was correctly simulated also in the *eb* hollow region where only the solenoid magnetic field is acting.

In Fig 2, the simulation results of the test particle transverse positions, *x* and *y*, (a), and their transverse velocities, v_t, (b), *vs Ns* (integration step number) are shown. From these results , it can be noticed that test ion motion is consistent with the forces involved. In fact, they oscillate in the *eb* potential well, placed in the centre of the pipe (*x=y=0*), and in the solenoid field but when they move in the hollow region, where only the solenoid field acts, they have a constant radial velocity (see fig. 2 b)) as expected since the magnetic field does not change the velocity module. This indicates that the routine solving the motion eq.s (1) works well also in the new conditions, when no rf field is present.

1 is presented. In those simulations, however, the 96% fixed 'overlap' assumed before has been modeled by considering, inside the *eb*, a cylindrical hole with a transverse section having a radius $r_h=0.024$ *cm,* corresponding to a *20%* of r_b. The results this time show that the case of an *eb* without the hollow part is sensibly different with respect to the case of an hollow *eb*, contrary to the results of the fixed 'overlap' simulation, shown in fig.1. The more accurate simulations obtained by taking into account the ion motion in the *eb* hollow region show a sensitive slow down of the charge breeding rate that can be better understood by observing the test particle ion motions at all along the simulation time (*~1.5 ms*), as it will be discussed later. However, it should be mentioned that an unexpected behavior in some test ion motion was observed, when analyzing the complete simulation time.

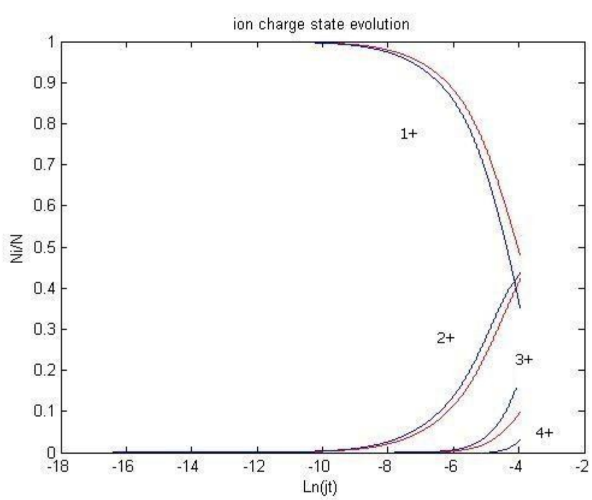

Fig. 3

The test particle transverse velocities for all the simulation time are shown in fig.4a). There, actually, the transverse velocities of the test particle *1* and *2* present the expected behavior, that is, ions oscillating with constant amplitudes. In fact, although at the beginning of the simulation decreasing amplitude oscillations are observed, due to the space charge compensation that takes place during the ionization process [7], at a later time those amplitudes remain practically constant. That is the correct ion motion behaviour since in the motion equations considered above only conservative force terms are present after the space charge compensation. For test particle number 3, however, the transverse velocity presents damped oscillating amplitudes. More precisely, its amplitude decreases up to a small constant value different from zero in about *1ms* and then it remains constant. The oscillating amplitudes of the test particle 3, in fact, reduces a constant velocity in the presence of the only solenoid field.

The *3* test ion motion behavior cannot be explained by the only conservative forces present in the motion equations (1). However, since this kind of damping motion is found only for a hollow *eb*, it is reasonable to conclude that it is the hole itself inside the *eb* potential well that could induce a sort of 'out of phase' parametric resonance effect in the motion of some ions (see below).

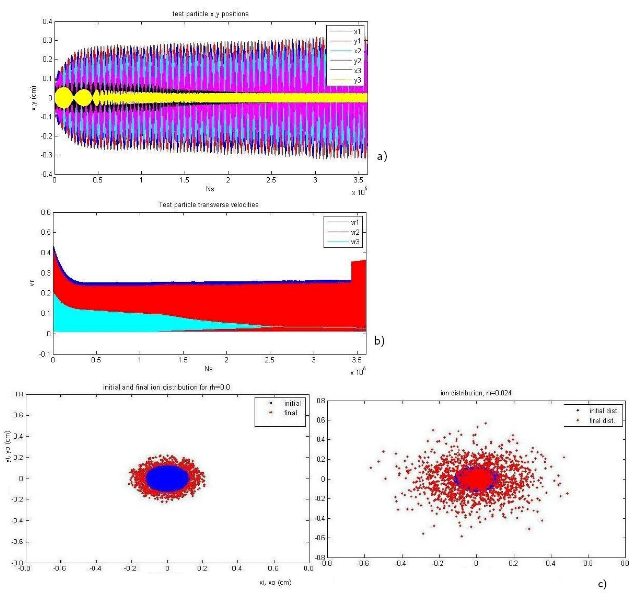

Fig. 4

Furthermore, on the other hand, in figure 4b), where the initial and final transverse ion position distributions are shown, it can be noticed that in the right final ion distribution (case with $r_h=0.024$ *cm*) there are particles placed at a very far distance from the potential well centre and therefore out of the *eb* cross section. Those positions are indicative of ions having had an oscillating motion with increased amplitudes (compare with the left figure where no hole is present in *eb*). Such an increase, on the contrary of what observed before, can be due to an 'in phase' parametric resonance effect.

In conclusion, it seems that in the simulations with a hollow *eb* some ions decrease their oscillating amplitude so to remain trapped inside the hole, while some other ions increase their oscillating amplitudes. Both those types of ions, of course, will contribute to slow down the charge breeding rate of the device as it has been confirmed by the results shown in fig. 3. It should be considered, in fact, that the ions with increasing oscillation amplitudes as well, will contribute to slow down the charge state increase rate, since they spend an increasing fraction of time outside the *eb*.
Just for comparison with fig. 4a), the simulation of the test particle transverse velocities for the case of an hollow *eb* has been carried out and their results are shown fig. 5. In that figure, as expected, neither dissipation nor excitation in the oscillating motion can be observed and all the ions, after the charge space compensation process, oscillate inside the *eb* potential well with constant amplitudes until the end of the simulation time.
All the simulation carried out until now to study the ion charge state breeding in the presence of a hollow *eb* has confirmed that some test particles could manifest the unexpected motion behaviour described before. Although the above observation could explain the simulation results of fig. 3, it remains yet to understand the mechanism that causes damped or increased oscillation amplitudes of the ions. In fact, as already observed above, from the motion equations (3) it can be seen that only the *eb* potential well and a constant, longitudinal, focusing magnetic field, which are both conservative forces, are applied on the ions. It is well known that in the presence of only conservative forces no damped or increasing ion oscillating motion should happen.

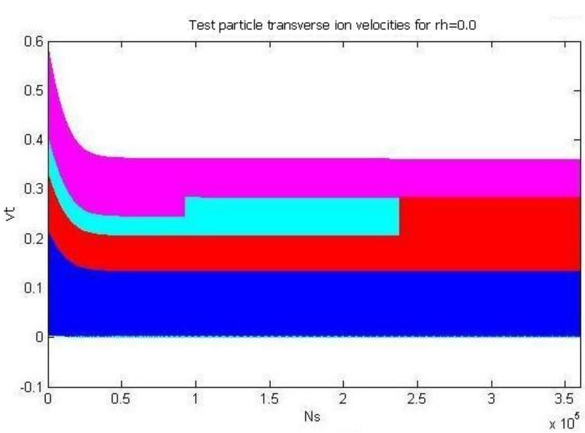

Fig. 5

From the simulations carried out up to now, it can be guessed that the presence of a hole in the *eb* introduces a discontinuity in the space charge potential well which seems to be felt by the ions, in that place, as an extra force that perturbs their motion. Such a force seems to act with different strengths on different oscillating ions, and it seems to have resonant features as it shows up when parametric resonances occur. In fact, since in the solution of the ion motion equation a finite integration step length, l_s, is used, it could happen that some ions, during their motion, see a potential well depth slightly different in each period.

More specifically, when the starting ion transverse position is inside the *eb* cross section and the final transverse position (after the integration step) results in the hollow region, that ion is treated by the code as if it was subjected to the potential well for all the steps, while, once inside the hollow region, no more electric field should act on it.
We have to notice, therefore, that the finite step length, l_s, used to integrate the motion eq.s (1), in correspondence of the sharp potential discontinuity due to hole could be, in any case, too long for a correct calculation. The above ion motion anomalies could then be due to the rough way of the code to take into account the discontinuity between the potential well and the hollow region where null space charge field is present. On the other hand, however, when l_s shorter than $0.004\ \mu s$ is used (value used in all the simulations shown above) no significant modifications on the global ion motion behavior were observed.
In practice, it is still not clear if the anomalies noticed on the ion motion behavior in our EBIS trap with the hollow *eb* is a physical or a numerical effect due to approximate calculations. In fact, the using, in the calculations, of an also very short l_s should be the same sensitive to the step present in the hollow eb potential shape (see fig. 2c). In any case, the experimental results [3] would clarify the dilemma.

CONCLUSIONS

The code package BRICTEST, developed to simulate the ion charge state evolution in BRIC an EBIS device with rf field for selective containment, after some small modifications, has been used for studying the ion charge state increase rate in an hollow gun EBIS.The simulation results show that the rough approximation with fixed ‘beam overlap’ between *eb* and ion beam transverse sizes give unreliable results. More accurate simulations, show that the ion charge state increase rate slow down sensibly with respect of the fixed ‘overlap’ case when a long enough interaction time is considered. Some ‘anomalies’, as the unexpected increased or damped oscillation amplitudes, are observed in the ion motion behaviour when an hollow *eb* is used.

Further simulations, carried out with smaller integration step length (up to 10 times less) to better understand if the above mentioned ion motion anomalies were related to parametric resonance effects or just an artefact of the numerical approximation did not reveal numerical errors, although such errors might still be the cause of the observed anomalies.

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